20,000 Leagues under the Sea: A Journey to the Future of Observing the Deep Oceans.

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Abstract - Future observations of the global ocean will move beyond measurements of the ocean surface topography, winds, roughness, sea surface temperature, and surface salinity to include in situ and remotely sensed measurements of the deep ocean. These important measurements will quantify the deep ocean circulation and its implication for the oceanic transport of heat, and the relationships between ocean circulation variability and climate change. New measurement technologies will include remote sensing measurements of ocean mass through global gravity observations, innovative measurement of oceanic vertical structure with satellite relayed data from in-situ profiling floats, and remote measurement of the ocean surface boundary layer at higher temporal resolution.

Introduction

In recent decades, tremendous advances have been made in observing various aspects of the ocean's state and ocean processes. Many of the most significant advances can be directly attributed to the development of techniques to remotely sense the ocean surface. With polar orbiting satellites that circle the earth roughly every 100 minutes, some with swaths that are thousands of kilometers wide, satellites provide the only appropriate sampling for observing and understanding large-scale processes.

To date, we have means of measuring a number of ocean surface parameters. Radar altimetry has enabled global ocean surface height measurement to approximately 2 cm; infrared remote sensing provides a means of determining ocean surface temperature with an accuracy of about 0.1 K; scatterometry gives us all-weather wind vectors accurate to 2 m/s and 20 degrees. Other types of microwave remote sensing can be used to estimate surface winds speeds to a similar accuracy. In addition, for the last several decades, passive microwave remote sensing has provided estimates of sea ice extent, ice concentration, ice type, and ice motion, while the more recent synthetic aperture radar provides high-resolution measurements of sea ice processes such as motion, growth, decay, and deformation.

While the operational and research contributions of these observations have been tremendous, they are limited to the surface – in most cases the top few millimeters – which can differ vastly from the meters or kilometers that may lie beneath. A more complete understanding of the ocean system requires a means of determining conditions well below the surface on the same large scales offered by satellites. Such observations and assessment continue to be a major challenge in oceanography.

Observations at depth

Currently, information on subsurface processes is provided by a limited ocean buoy network, traditional research vessel sampling, expendable temperature profilers on merchant ships and an emerging array of independent neutrally buoyant and profiling floats in the ocean. These floats are tracked acoustically and relay their data via polar-orbiting weather satellite to make it possible to get data from these expendable floats. The most important of the buoy networks is the TAO array in the tropical Pacific shown here in Fig. 1.

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Fig. The TAO Buoy Array

These buoys are instrumented to measure near-surface atmospheric parameters from the floating buoy (Fig. 2) as well as subsurface

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Fig. 2 TRITON Buoy

measurements made below the buoy along the mooring line and report these data in real-time. The tropical Pacific location of this mooring array provides an excellent monitor of El Nino conditions as they emerge and evolve. These moored buoy measurements are expanding, but are still relatively sparse. These measurements provide information from the surface to depths of as much as 1,000.

A more recent development is the ARGO profiling float that samples the internal ocean parameters while it ascends and descends in the ocean (Fig. 3).

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Fig. 3 Operation of an ARGO float

Instrumented to measure temperature, salinity and depth as well as cycle the float up or down in the water column (Fig. 4) these floats are able to operate in the open ocean up to a year and longer. The reliability of these floats has been demonstrated with existing programs and future arrays will provide greater global coverage.

Plans call for the eventually and continual deployment of as many as 3,000 ARGO floats to profile the ocean for operational purposes much like an array of installations, mostly at local airports, monitors the weather and climate conditions of the Earth. Taken together data from these floats will provide us with the first near real-time mapping of the subsurface ocean and its parameters. This structure can then be related to the subsurface ocean currents that redistribute oceanic properties the distribution of which has been used for years to indicate the flow paths of the subsurface ocean currents.

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Fig. 4 ARGO Float

It is very difficult for satellite sensors to penetrate the ocean's surface and hence measure in situ oceanic properties. In the infrared the thermal emissions sensed by the satellite sensors are emitted from the 10-micron thin surface layers. The active and passive microwave probably extends this to a couple of millimeters depth. The difference between these two satellite derived surface temperatures is related to the heat and momentum fluxes between the ocean and the atmosphere.

Radar altimetry (Fig. 5) has given us a means to monitor variations in the ocean's surface topography related to geostrophic ocean currents. These measurements are all relative to a poorly known geoid but gravity missions such as GRACE are starting to supply an improved gravity field to better describe this geoid contribution to the altimeter signal.

Planned Wide Swath Ocean Altimetry (WSOA) will make it possible to map mesoscale resolution geostrophic surface currents while at present we can only resolve the large-scale currents.

It should be noted that remote sensing of the ocean's surface can be used in conjunction with numerical models to gain additional information about the ocean's interior. By assimilating ocean surface

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Fig. 5 TOPEX/Poseiden Altimetric Satellite

observations from satellites into physical models of the ocean's dynamics and thermodynamics it is possible to learn a great deal about the internal ocean structure as constrained by the surface satellite data. This type of analysis is likely to continue to improve in the future.

A Vision for the Future

Many measurement and modeling improvements are anticipated for the near and distant future. The worldwide array of ARGO floats is being implemented and regional efforts are underway to expand the number of moored buoys reporting both near-surface atmospheric conditions and subsurface oceanic observations. This emphasis in regional ocean measurements is a direct response to the economic potential of the coastal regions and their direct societal relevance.

In the open ocean a global observing system is being proposed that will consist of moored buoys, ship surveys, and expendable measurements from merchant ships. Coupled with new and existing satellite measurements this new global observing system should yield unprecedented resolution of the ocean's behavior and allow us to transition from a limited sample research mode into a fully operational system.

New gravity satellite missions will continue to improve our knowledge of the Earth's geoid helping us to better estimate the absolute value of geostrophic currents from satellite altimetry. Wide swath altimetry and the new delay Doppler altimetry will give us greater spatial resolutions while maintaining the high height accuracy. Thus, we will be able to map and monitor the global mesoscale ocean circulation on a real-time basis.

The planned Aquarius salinity satellite mission will provide a direct measurement of surface salinity. Aquarius measurements will demonstrate the value and application of this new sensing of ocean surface salinity. As with other surface measurements it may be that the greatest utility of these data is in conjunction with numerical models to learn more about the state of the ocean's interior.

A significant challenge for the future is the resolution of the diurnal cycle at the ocean's surface. Much of what has been learned about the ocean from satellites has been based on polar-orbiting satellite data. These data naturally alias the diurnal signal at the ocean's surface making it impossible to resolve this important fundamental oscillation.

Only a geostationary satellite can provide the temporal resolution needed to properly resolve the diurnal cycle. Since this cycle has both thermal infrared and reflectance surface expressions it would be best to have a geostationary sensor that can measure in both the thermal infrared and in the ocean color bands. In this way this future geostationary sensor could resolve both the diurnal thermal variations associated with air-sea heat and momentum fluxes while also making it possible to view the diurnal variations due to biological activity.

Another possible future satellite measurement is a LIDAR to directly observe the upper ocean mixed layer. A proof of concept would fly in low Earth orbit to maximize the return from the laser but in the future such a LIDAR mixed layer measurement could be coupled with the geostationary infrared sampling to better resolve the behavior of the upper ocean.

Interferometric synthetic aperture radar (InSAR) has the potential for mapping ocean surface properties under all weather conditions with a spatial resolution not possible with passive microwave methods. A lot of basic research is still needed to understand the nature of SAR returns for the ocean's surface.

Conclusions

While present satellite remote sensing is primarily restricted to measurements of the ocean's surface future satellites will hopefully supplement the planned expansion of in situ sensing of the ocean's interior. New missions for surface salinity, improved gravity sensing, mixed layer measurements and the diurnal cycle all have the potential for greatly expanding our understanding of the workings of the ocean.